Closed-Loop Control
of Functional Neuromuscular Stimulation

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1. SYNTHESIS OF UPPER EXTREMITY FUNCTION

The overall goals of this project are (1) to measure the biomechanical properties of the neuroprosthesis user's upper extremity and incorporate those measurements into a complete model with robust predictive capability, and (2) to use the predictions of the model to improve the grasp output of the hand neuroprosthesis for individual users.

1. a. BIOMECHANICAL MODELING: PARAMETERIZATION AND VALIDATION

Purpose

In this section of the contract, we will develop methods for obtaining biomechanical data from individual persons. Individualized data will form the basis for model-assisted implementation of upper extremity FNS. Using individualized biomechanical models, specific treatment procedures will be evaluated for individuals. The person-specific parameters of interest are tendon moment arms and lines of action, passive moments, and maximum active joint moments. Passive moments will be decomposed into components arising from stiffness inherent to a joint and from passive stretching of muscle-tendon units that cross one or more joints.

Progress Report

1. a. i. MOMENT ARMS VIA MAGNETIC RESONANCE IMAGING

Abstract

We have established a method of measuring the alignment of joint moment axes and kinematic axes, and have completed imaging measurements in one able-bodied individual. A manuscript is being prepared describing our previously reported wrist moment sensor.

Progress Report

In this quarter, we constructed a splint with MRI visible markers (vitamin-E capsules) as well as a keyed-in mounting platform with infrared LEDs. The person wears the splint when the wrist and hand are imaged, and when moments are measured. When collecting MRI images, we find the coordinates of the vitamin E capsules relative to the segmented bones. When making moment measurements, we mount the led arrays and the wrist moment sensor to the same splints. The wrist angle is then measured by tracking the leds with an Optotrak system, and the axes of the sensor relative to the LEDs allows direct calculation of the moment sensor axes relative to the bone segments. This system assumes that the splints are fixed relative to the bones.

We are in the process of testing the complete system in an able-bodied individual. To date, we have collected and analyzed the MRI data that will allow us to calculate the ECU moment arm for movements in the radial-ulnar plane, and the ECRB moment arm in the flexion/extension plane. The values are in the range reported in the literature (ECU radial/ulnar moment arm is rougly twice as large as ECRB felxion/extension moment arm). We will also measure ECU moments in the same individual in late May. The completet set of measurements will allow us to predict the moment that would be produced by a tendon transfer of the ECU to ECRB in this individual, with a range of reattachment lengths. Of course, the transfer will not be performed in this person, but this test and analysis are essential The values are in the range reported in the literature (ECU radial/ulnar moment arm is rougly twice as large as ECRB felxion/extension moment arm). We will also measure ECU moments in the same individual in late May. The completet set of measurements will allow us to predict the moment that would be produced by a tendon transfer of the ECU to ECRB in this individual, with a range of reattachment

lengths. Of course, the transfer will not be performed in this person, but the test and analysis are essential to demonstrate the feasibility and accuracy of the methodology.

We also completed a major portion of the wrist moment sensor paper, but will wait for the ECU moment measurements to complete the paper. Thus, we expect to complete this paper by the end of the next quarter.

Plans for next quarter

We expect to make wrist moment measurements on the same able-bodied individual whose moment arms we have already measured. These moments will allow us to complete the moment sensor paper in the next quarter, to predict the results of tendon transfer, and to analyze the errors involved in the whole process.

1.a.ii. PASSIVE AND ACTIVE MOMENTS

Abstract

Previously, we reported that the position of the metacarpal phalangeal (MP) joint of the long finger had a very strong influence on the passive properties recorded for the MP joint of the index finger. It appears that this effect is primarily due to the stretching of the skin between the fingers. It is important to identify this effect in order to make accurate clinical measurements. To our knowledge, this effect has not been reported previously in the literature, and textbooks explaining how to make passive range of motion measurements ignore this effect. During this quarter we have worked on modifications to our measurement apparatus in order to enable us to obtain additional information regarding this effect.

Purpose

The purpose of this project is to characterize the passive properties of normal and paralyzed hands. This information will be used to determine methods of improving hand grasp and hand posture in FES systems.

Progress Report

During the previous quarter, we verified that the angle of the long finger MP joint has a significant effect on the passive properties of the index finger MP joint. The results indicate that the effect is significant over the whole range of long finger positions, and this effect has the same order of magnitude as the effect of wrist angle. This effect can occur either directly through the skin or through linkages between the tendons and muscles (especially in the extensor digitorum communis). The effect that we have measured appears to be due directly to stretching the skin between the two digits, at least in some patients.

The direct cause for the influence of adjacent digits can be determined by measuring the effect of the position of the MP joint of one finger on the PIP joint of an adjacent finger, or by measuring the effect of the positions of adjacent PIP joints on one another. By measuring the passive properties of the PIP joint, the potential effect of stretching the skin is essentially eliminated, leaving only the effect of changing tendon tensions. During this quarter, we have worked on developing simple splints that will allow us to position the PIP joint at three different joint angles (0, 45 and 90°). These splints will then be attached to our passive moment measurement apparatus. We will use the same experimental protocol as we used to establish the initial effect.

Plans for Next Quarter

During the next quarter, we will perform experiments to examine the effect of adjacent digit position on passive properties. These experiments will focus on the effect of the PIP joint position.

1. b. BIOMECHANICAL MODELING: ANALYSIS AND IMPROVEMENT OF GRASP OUTPUT

Abstract

Computer model simulations of the Br-ECRB tendon transfer indicate that biomechanics plays an important role in wrist function after transfer. Simulations also indicate that the way in which the transfer is tensioned (i.e., whether a tight or slack transfer is performed) influences both the active wrist extension that is restored by the surgery and the degree of passive, gravity-assisted wrist flexion that can be achieved after surgery. It is important to understand how well the biomechanical model represents wrist function in patients. Quantifying wrist function after tendon transfer surgery is a critical step for understanding the function predicted based on biomechanics and wrist function after tendon transfer surgery.

Objective

The purpose of this project is to use the biomechanical model and the parameters measured for individual neuroprosthesis users to analyze and refine their neuroprosthetic grasp patterns.

In the past quarter, we have evaluated how the passive moment-generating capacity of the tight and slack Br-ECRB transfer (described in previous progress reports) influences gravity-assisted wrist flexion. The net passive moment at the wrist joint (before a Br-ECRB transfer) was compared to the passive wrist extension moment generated by the transfer to estimate the range of wrist postures where gravity-assisted wrist flexion is possible.

Progress Report

In the past quarter, we have focused on the experimental set-up for the strength measurements in neuroprosthesis users. We have spent time expanding and organizing the software for data collection and post-processing. The current software will be easier to adapt to the goals of different protocols and the post-processing software has been re-organized to allow us to more quickly process, plot, and summarize the results after an experiment. We have also focused on the devices for experimental measurements, evaluating a BioDex apparatus for the measurement of passive joint properties, and completing calibration and accuracy evaluations of the elbow moment transducer. In addition, we have started to evaluate available patient databases to identify differences in function after tendon transfers in current patients, and to identify good candidates for further study. The calibration of the elbow moment transducer and an initial summary of the patient data are described in more detail below.

Calibration of the Elbow Moment Transducer

A moment transducer has been developed to measure the elbow flexion-extension moments generated via functional electrical stimulation or voluntary contraction in tetraplegic subjects, and has been described in previous progress reports. We recently completed a rigorous calibration of this device, to address concerns regarding its accuracy in an experimental situation. The calibrations were also performed because various adjustments have been made to the device since the last calibration. The adjustments to the device improved the mechanism that locks joint position in place; in previous work we found the locking mechanism to be unable to withstand higher loads. While we did not expect these adjustments to alter the calibration of the device, it did allow us to test device performance at higher loads.

The calibration experiments were designed to test whether the gain of the transducer depends on:

- the direction of the applied load
- the position of the elbow joint
- the presence of off-axis loads
- the position of the shoulder joint

The transducer was secured to an “arm”, made from two aluminum beams connected by a hinge joint. Moments were applied to the transducer by loading the aluminum arm with a known mass at a specified distance from the hinge joint. To test whether the gain of the transducer varied with the direction of the applied load, loads between 0 Nm and 15 Nm were applied in the extension direction, and loads between 0 Nm and 8 Nm were applied in the flexion direction. To test whether the gain of the transducer varied with elbow joint position, flexion and extension loads were applied in three different joint positions (60˚, 90˚, and 120˚). To test whether the gain of the transducer varied with off-axis loads, the transducer was loaded with elbow extension and pronation-supination moments simultaneously. In a second test of the sensitivity of the transducer to off-axis loads, the transducer was loaded with elbow extension and varus-valgus moments simultaneously. To test whether the output of the transducer was sensitive to shoulder position, the aluminum arm was positioned to simulate 90˚ shoulder abduction (both beams were parallel to the ground) and 45˚ shoulder abduction (the beam representing the “upper arm” was at a 45˚ angle from horizontal).

A linear regression model of covariance was used to define the relationship between the voltage output of the transducer and the applied moment. The regression analysis demonstrated that the direction of the applied moment, the position of the elbow joint, the presence of the off-axis loads, and the position of the shoulder joint all significantly affect the voltage output of the transducer. However, we determined that the position of the elbow joint, the presence of off-axis loads, and the position of the shoulder joint did not influence the transducer output in a clinically meaningful way. This was done by comparing the 95% prediction intervals about the moment estimated from regression equations that include each of these factors to the 95% prediction intervals about the moment estimated from the regression equation which relates voltage and the applied flexion or extension moment. The width of the prediction interval about the estimated moment did not narrow substantially if the other factors were taken into account. The calibration equations for the elbow moment transducer in flexion and extension, and the accuracy estimates are given in Table 1.b.I.

Table 1.b.I. Calibration Summary for the Elbow Moment Transducer

	Calibration Equation	Accuracy	
		(moment > 1 Nm)*	(moment ≤ 1 Nm)†
Extension	$M = 5.3660(V) - 0.0339$	≤1.03% of moment	0.01 Nm
Flexion	$M = 5.0077(V) - 0.0109$	≤1.24% of moment	0.02 Nm

*half of the width of the 95% prediction interval, expressed as a percentage of the predicted moment
†standard error of the predicted moment

Table 1.b.II. Summary of Wrist Passive Range of Motion Measurements Reported by Johnson et al. (1996)

Patient	Difference Between Pre- and Post-Operative ROM* extension	flexion
1	0	-15
2	-3	-18
3	-5	-19
4	0	-13
5	-3	-15
6	-2	-10
7	-4	-5
8	-4	-18
9	-8	-15
Mean	-3.2	-14.2
S.D.	2.5	4.4

**positive numbers indicate an increase in passive ROM post-operatively*

Evaluating the Br-ECRB tendon transfer in patients

The function of the Br-ECRB tendon transfer has been evaluated in previous studies. Johnson *et al.* (1996) reported the pre-operative and post-operative passive range of motion at the wrist, manual muscle strength grades of the brachioradialis at the elbow joint and the wrist extensors pre-operatively, and the manual muscle strength grade of the wrist extensors post-operatively. This study showed that post-operative wrist extension improved in the 9 out of 9 patients evaluated. Also, the passive range of wrist flexion decreased an average of 14.2˚ post-operatively, compared to the pre-operative range of motion (Table 1.b.II). This result supports our computer simulations that indicate a tight transfer can limit gravity-assisted wrist flexion post-operatively. The passive range of wrist extension also decreased slightly (3.2˚) post-operatively.

A follow-up of Br-ECRB tendon transfer patients is being carried out in our clinical laboratory. We compared the data collected from our patients to the results reported in the work of Johnson *et al.* (1996). Pre-operative and post-operative passive range of motion data was available for 9 patients. In one patient, passive range of motion data was available for both the left and right arms. The average time between pre- and post-operative tests was 24.3 months (range 6-57 months). The passive range of wrist flexion decreased post-operatively in 9 of the 10 limbs evaluated (Table 1.b.III). In one patient (15) the passive range of wrist flexion did not change. Although there is a greater degree of variability in the data from our patient population, these results are in agreement with the results reported by Johnson *et al.* (1996). Thus, our patient data also supports computer simulation results that indicate a tight transfer could limit gravity-assisted wrist flexion. In seven subjects, the passive range of wrist extension either decreased or did not change post-operatively, as reported by Johnson *et al.* However, the decreases in wrist extension were generally larger in these seven subjects than the subjects in the Johnson study. In addition, the passive range of wrist extension increased in three of the subjects from our population. Currently, the effect of the transfer on the passive range of wrist extension remains unclear. This issue could be further investigated using the biomechanical model.

At this point, the most straightforward result from the passive range of motion data is that the Br-ECRB transfer is associated with a decreased passive range of wrist flexion. Based on the computer simulation results described in previous progress reports, this could indicate that surgeons typically perform a *tight* Br-ECRB tendon transfer. That is, the brachioradialis is attached to the ECRB at a length that is long enough for the muscle to generate substantial passive force. Our computer simulations imply that a tight transfer can provide wrist extension in flexed elbow postures, while a slack transfer can not. In two subjects (9, 15), the active range of wrist extension was tested in different elbow postures (Fig. 1.b.1). Subject 9 was able to maintain an extended wrist at 0˚ elbow flexion (full extension), 90˚ elbow flexion, and 150˚ elbow flexion. Subject 15 was able to maintain wrist extension at 0˚ elbow flexion, but couldn't extend the wrist even to the neutral position (0˚ wrist flexion) at 90˚ elbow flexion. Evaluating these results in light of our computer simulations, we could hypothesize that Subject 9 has a tight transfer while Subject 15 has a slack transfer. The passive range of motion data also supports this

Table 1.b.III. Summary of Wrist Passive Range of Motion Measurements: FES Center Patients

Patient	Difference Between Pre- and Post-Operative ROM* extension	flexion
2	-16	-29
6L	-20	-17
7	-15	-9
8	-12	-46
9	-3	-15
13	0	-20
14L	-24	-27
6R	11	-4
11	15	-61
15	10	0
Mean	-4.2	-22.1
S.D.	14.3	19.9

**positive numbers indicate an increase in passive ROM post-operatively*
The portion of the table that is shaded is to highlight the 3 subjects where the passive range of wrist extension increased post-operatively.

hypothesis. Subject 9 lost 15˚ of passive wrist flexion post-operatively, implying the Br-ECRB transfer generated a passive wrist extension moment post-operatively. Subject 15's passive range of wrist flexion did not change post-operatively, implying the Br-ECRB transfer did not generate a passive wrist extension moment post-operatively.

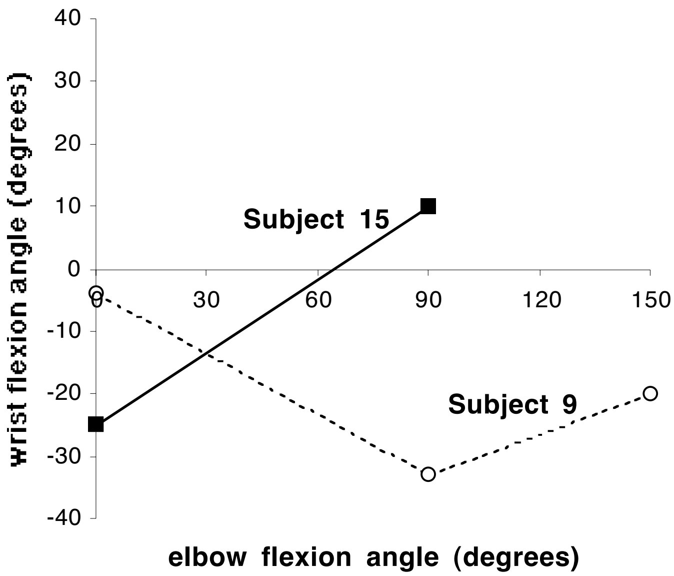

Figure 1.b.1. Wrist flexion angle that could be maintained in different elbow positions by subjects 9 and 15 from our patient database. Positive wrist flexion angles indicate the wrist is flexed, negative angles indicate the wrist is extended. Subject 9 can maintain wrist extension over a full range of elbow positions. Subject 15 cannot maintain an extended wrist as the elbow is flexed.

Plans for Next Quarter

In the past quarter, we have focused on the experimental set-up for strength measurements. We have also evaluated available patient data, and have identified two subjects in our database that have displayed functional characteristics predicted by our model.

In the next quarter, we will continue to evaluate our patient database to identify other subjects for further study. We will further investigate the differences in passive range of motion that have been observed across subjects. For example, we will investigate whether the patients who lost passive wrist extension post-operatively also have had procedures that could limit passive extension. We would expect to find that the patients that lost passive wrist extension also underwent tendon transfers that restore finger flexion, while those that gained passive wrist extension did not. In addition, we will evaluate the passive range of motion database for patients who did not undergo a Br-ECRB transfer, to test if patients who do not have the Br-ECRB transfer maintained the range of passive wrist flexion post-operatively. Videotapes of patients performing functional tests are available. In the next quarter, we plan to use these videotapes to evaluate wrist function in Subject 9 and Subject 15. By continuing to evaluate the available patient data, we plan to categorize patients as having either "tight" transfers or "slack" transfers. In the future, elbow strength, wrist strength, and passive wrist properties will be measured in these subjects to test whether our categorization based on passive range of motion and functional tests agree with the biomechanical model.

In the next quarter, we will continue biomechanical analysis of the transfer. Specifically, we will perform sensitivity tests of the current simulations and simulate wrist function after a Br-ECRB transfer that includes transferring the Br origin distally on the humerus. Also, we plan to submit a paper to the Journal of Hand Surgery summarizing our analysis of the Br-ECRB transfer by the end of next quarter.

References

Johnson, D. L., Gellman, H., Waters, R. L., and Tognella, M. (1996) Brachioradialis transfer for wrist extension in tetraplegic patients who have fifth-cervical-level neurological function. *Journal Bone Jt Surg* **78-A**, 1063-1067.

2. CONTROL OF UPPER EXTREMITY FUNCTION

Our goal in the five projects in this section is to either assess the utility of or test the feasibility of enhancements to the control strategies and algorithms used presently in the CWRU hand neuroprosthesis. Specifically, we will: (1) determine whether a portable system providing sensory feedback and closed-loop control, albeit with awkward sensors, is viable and beneficial outside of the laboratory, (2) determine whether sensory feedback of grasp force or finger span benefits performance in the presence of natural visual cues, (of particular interest will be the ability of subjects to control their grasp output in the presence of trial-to-trial variations normally associated with grasping objects, and in the presence of longer-term variations such as fatigue), (3) demonstrate the viability and utility of improved command-control algorithms designed to take advantage of forthcoming availability of afferent, cortical or electromyographic signals, (4) demonstrate the feasibility of bimanual neuroprostheses, and (5) integrate the control of wrist position with hand grasp.

2. a. HOME EVALUATION OF CLOSED-LOOP CONTROL AND SENSORY FEEDBACK

Abstract

The purpose of this project is to deploy an existing portable hand grasp neuroprosthesis capable of providing closed-loop control and sensory feedback outside of the laboratory. We have completed the development of a stand alone, analog, single channel stimulator for grasp-force feedback. A new α-prototype was completed in the CWRU Technical Development Laboratory and was tested for long-term (day-long) wear on able-bodied subjects. Similar tests will be completed on neuropsrosthesis users in the next quarter prior to producing 5-6 units for field deployment.

Purpose

The purpose of this project is to deploy a portable hand grasp neuroprosthesis capable of providing closed-loop control and sensory feedback outside of the laboratory. Our goal is to evaluate whether the additional functions provided by this system benefit hand grasp outside of the laboratory.

Progress Report

We have completed a new α-prototype of the battery-powered, single-channel, force-feedback stimulator. This pre-production unit is fabricated on a custom printed circuit board (in contrast to the hand-wired prototype described previously) and with a combination of surface mount and discrete components. With some modifications, the new design will be suitable for production. The high-voltage power supply has been modified slightly from that described previously for more robust performance, but continues to provide a 120V overhead. The new unit measures 12 × 6 × 3 cm and weighs 185g (including 9V battery, sensor, and electrode cable). The unit is small enough to be worn on a belt, and may even be strapped to the upper arm (to minimize sensor and electrode cable lengths) for an entire day, as verified through testing on able-bodied subjects.

Plans for Next Quarter

We will make a set of short-run (1 day) field tests of the α-prototype on neuroprosthesis users in order to detect and correct remaining design problems. We are particularly concerned about the ergonomics of the sensor and electrode. Pending successful completion of the tests, we will produce 5-6 units for field deployment.

2. b. INNOVATIVE METHODS OF CONTROL AND SENSORY FEEDBACK

2. b. i. ASSESSMENT OF SENSORY FEEDBACK IN THE PRESENCE OF VISION

Abstract

The purpose of this project is to develop a method for including realistic visual information while presenting grasp-force feedback information simultaneously, and to assess the impact of force feedback on grasp performance in the presence of such visual information. In this quarter, we revised our previous protocol so that targets in the simulated acquire-and-hold task were defined in terms of force rather than by command signals, and we re-acquired complete evaluation data from 7 able-bodied subjects. As before, grasp-force feedback significantly improved both the success rate in the acquire-and-hold task as well as the failure identification rate. This completes the initial study, and a manuscript will be submitted next quarter. We will also initiate continuing studies on the effects of object stiffness and task parameters.

Purpose

The purpose of this project is to develop a method for including realistic visual information while presenting other feedback information simultaneously, and to assess the impact of feedback on grasp performance. Vision may supply enough sensory information to obviate the need for supplemental proprioceptive information via electrocutaneous stimulation. Therefore, it is essential to quantify the relative contributions of both sources of information.

Progress Report

We presented data in the previous report from a complete set of experiments using the simulated acquire-and-hold task to demonstrate the effects of grasp force feedback in the presence of vision; and we were preparing a manuscript describing those results. However, we discovered a conceptual flaw in the implementation of the acquire-and-hold task that required a revision of the protocol and a complete replication of those experiments.

The original version of the acquire-and-hold task *derived* target forces from a target window *defined* in terms of the command signal. For example, the nominal target was chosen as 70±10% command. This protocol was formulated for the original evaluations because we had intended to test closed-loop control as well as sensory feedback. It was essential for the former to maintain a consistent range of command signal inputs for different control schemes and load compliance. The protocol is inappropriate for sensory feedback, however, since the resulting targets do not represent properties of the object *per se*. The forces corresponding to the target commands were derived using the average recruitment functions (force vs command functions) calculated across the library of video clips used in the evaluation. As illustrated in the figure below (taken from the actual data used in the initial series of experiments), systematic changes in the command targets produced irregular changes in the force targets due to the shape of the recruitment function. Moreover, since the recruitment function for each video clip differed slightly from the average, the defined command targets would correspond to different force, and hence different force feedback signals, in every trial. Under these conditions, it would be possible for subjects to fail a task in one trial even though they produced the same force and received the same feedback stimulus as in a previously successful trial. It is interesting that feedback improved performance in the task (on average) in spite of this trial-to-trial variability.

We corrected the methodological error by re-defining target windows in terms of force directly. The evaluations were repeated on the same able-bodied subjects who completed the original evaluations, but with a new library of video clips (we surmised that subjects might have become overly familiar with the set used previously). We note that the new set of clips did not have the non-monotonic recruitment function characteristic of the prior set. The results did not differ substantially from those described previously. Feedback again improved the success rate equally at all window sizes and it improved the failure identification rate. Details of the new evaluations will be submitted next quarter as a manuscript submitted to IEEE Transactions on Rehabilitation Engineering.

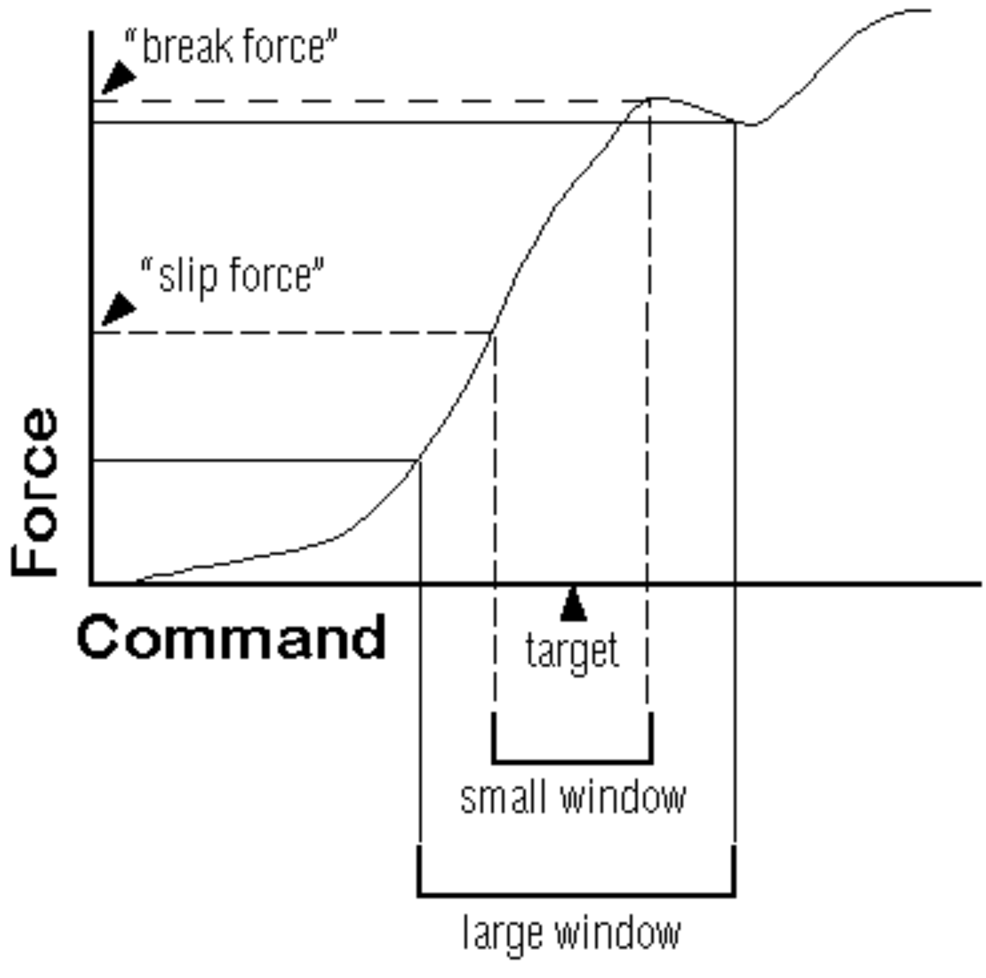

Fig. 2.b.1 Illustration showing the irregular force windows that result from defining window boundaries as commands and calculating forces using an erratic recruitment function.

Plans for Next Quarter

We will submit a manuscript describing the simulation and evaluation system and the results of the revised experiment to IEEE Transactions on Rehabilitation Engineering. We will also initiate continuing studies on the effects of object and task parameters on the relative contributions of visual and grasp force feedback.

2. b. ii. INNOVATIVE METHODS OF COMMAND CONTROL

Abstract

The purpose of this project is to develop new command control algorithms that will make control of neural prosthetic hand grasp simpler and more effective. During this quarter the influence of a delay between the command and the output was investigated. The addition of a delay as large as 333 ms had no significant effect on performance. The efficacy of two locking algorithms, normalized velocity and peak detection was also evaluated. When the data was pooled across subjects (n=3), the locking algorithm did not have a significant effect on performance. However, there were significant variations between subjects.

Purpose

The purpose of this project is to improve the function of the upper extremity hand grasp neuroprosthesis by improving user command control. We are specifically interested in designing algorithms that can take advantage of promising developments in (and forthcoming availability of) alternative command signal sources such as EMG, and afferent and cortical recordings. The specific objectives are to identify and evaluate alternative sources of logical command control signals, to develop new hand grasp command control algorithms, to evaluate the performance of new command control sources and algorithms with a computer-based video simulator, and to evaluate neuroprosthesis user performance with the most promising hand grasp controllers and command control sources.

Progress Report

1. Effect of Input-Output Delay on Performance

The influence of a delay between the input command and the output position/force was tested using the video-based simulator. In either case ("delay" or "no delay"), the force and hand position were determined by the position of the subject's shoulder. The command outputs were stored in an array for future lookup. In the case of "delay" the output force and position were delayed by up to 333 ms. This delay allows the processor to read and interpret locking signals before they affect the hand output. In the case of "no delay" the force and position followed the shoulder command directly. In this case the processor looks back at previous data to decide if a lock signal was present, and thus lock commands, i.e., a quick shoulder elevation, also appear at the output as a change in position/force.

The influence of an input-output delay was tested using the baseline proportional command control algorithm. The acquire and hold evaluation task used in previous simulator tests was used. This task required the subject to attain a certain output force within a set time period (3 s) during the acquire stage and to maintain that force within a window during the hold stage (3 s). Four command window sizes were tested on each of three subjects with and without delay. The delay imposed was determined by the parameter initialization routine run at the start of each session (see QPR 11). The results (fig. 2.b.ii.1) indicate that the presence of a delay did not have a significant effect on the performance of the acquire and hold task (ANOVA, p=0.2964). Because the "no delay" algorithm causes the lock command to change the output, and the delay did not degrade performance, the "delay" algorithm will be used in future command control evaluations.

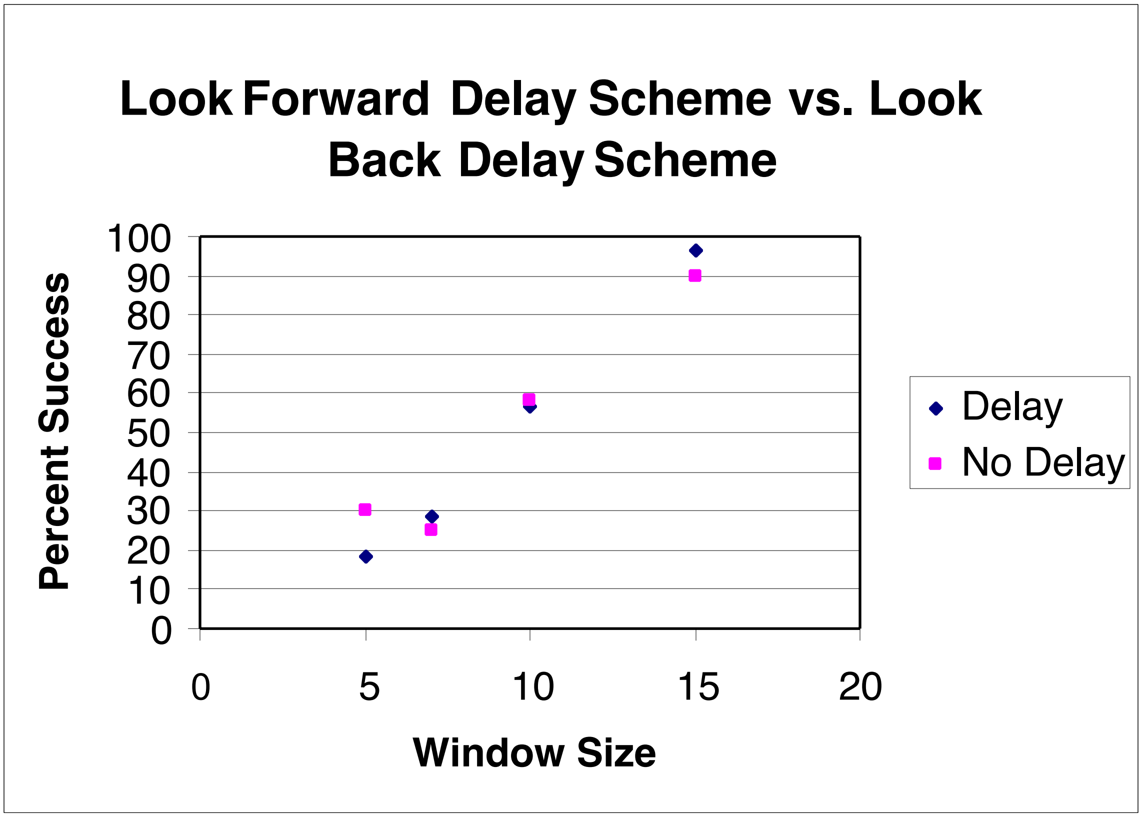

Figure 2.b.ii.1 Percent success as a function of command window size for an acquire and hold task. Data are from 3 subjects each conducting 20 trials per command window size either with or without a delay between the input and output. The presence of a delay had no significant effect on performance.

2. Efficacy of Two Different Algorithms to Lock Command Level

We tested combinations of two different locking algorithms and the two delay schemes. The two locking algorithms, as described previously (see QPR 11), were the peak detection algorithm (PD) and the normalized velocity (NV) algorithm. Subjects using the simulator were required to close the hand to a specific position/force, and to lock the hand at that position/force when they heard a beep. The force window size was set large enough that accuracy of shoulder position was not a concern. This method allowed the evaluation to account for inadvertent locks as well as missed locks when the subject was not able to lock the hand on the first try. Each of three subjects performed 20 trials under each condition. When the data were pooled, neither delay nor type of lock algorithm had a significant effect on lock success (ANOVA, $p=0.8427$). However, the results varied significantly (ANOVA, $p=0.0006$) across subjects (fig. 2.b.ii.2). These results suggest that the best locking algorithm may be subject specific, and that further testing is required if only a single algorithm is to be selected for evaluation of command control requiring a voluntary lock signal.

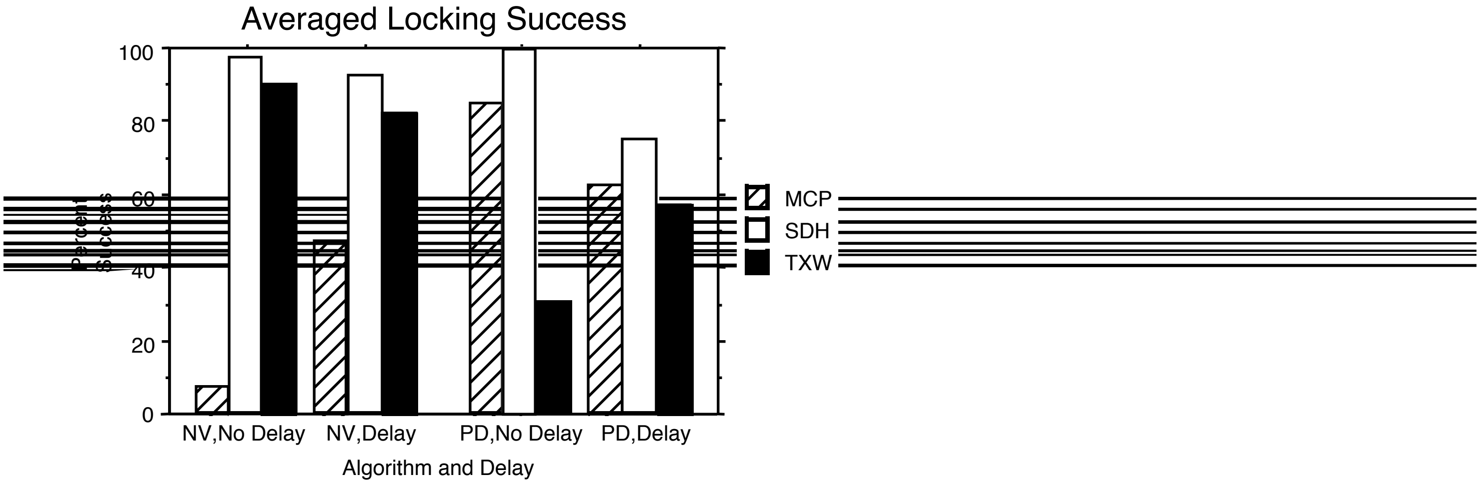

Figure 2.b.ii.2 Percent success in achieving lock using two different locking algorithms (NV=normalized velocity, PD=peak detection) for three subjects. Each subject performed 20 trails for each condition. When the data were pooled the performance did not depend on the locking algorithm or the presence of a delay. However, the performance varied significantly across subjects.

3. Design of a New Task for Controller Evaluation

One of the anticipated advantages of proposed command control algorithms is that they allow the user to adjust easily the command output after locking. The present acquire and hold task, as described above, does not require that the force be adjusted after a lock is initiated. Preliminary testing (see QPR 10, 11) has thus demonstrated that the acquire and hold task does not effectively test the efficacy of the new command control algorithms. Therefore, a new evaluation task has been designed. This new task is illustrated in figure 2.b.ii.3. During the acquire phase (3 s), the subject must attain a force within a specified window. During the lock phase (6 s), the subject must lock the command to maintain the output force within the specified window. During the adjust phase (6 s), the subject must adjust the force either by unlocking and adjusting the command level to produce the a force within the new window or by using an adjustment feature in the new command control algorithms.

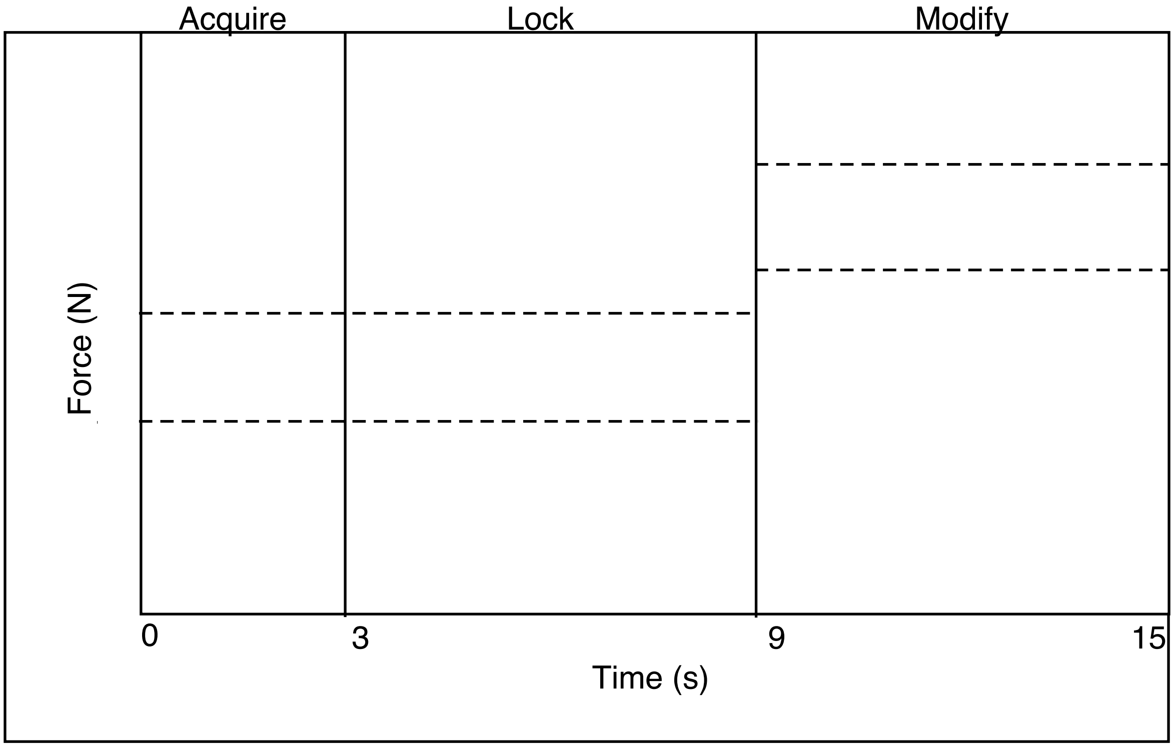

Figure 2.b.ii.3 The new acquire-hold-modify task to be used with the video simulator to evaluated the efficacy of new command control algorithms.

Plans for Next Quarter

Effort in the next quarter will focus on evaluation of new command control algorithms using the video simulator. Specifically, the new evaluation task will be implemented in the evaluation software, testing of the locking algorithms will continue, and standardized testing of the eight command control algorithms already implemented in the software will be conducted.

2. b. iii . INCREASING WORKSPACE AND REPERTOIRE WITH BIMANUAL HAND GRASP

Abstract

An article based upon the information presented at the NIH Neural Prosthesis Workshop in October, 1998, was written and submitted for publication to NeuroReport. This article, entitled *An EEG-based Controller for a Hand Grasp Neuroprosthesis,* has been accepted and will be published in the June, 1999, issue of the journal.

Purpose

The objective of this study is to extend the functional capabilities of the person who has sustained spinal cord injury and has tetraplegia at the C5 and C6 level by providing the ability to grasp and release with both hands. As an important functional complement, we will also provide improved finger extension in one or both hands by implantation and stimulation of the intrinsic finger muscles. Bimanual grasp is expected to provide these individuals with the ability to perform over a greater working volume, to perform more tasks more efficiently than they can with a single neuroprosthesis, and to perform tasks they cannot do at all unimanually.

Progress Report

An article based on the information presented at the Neural Prosthesis Workshop in October of 1998 was compiled and submitted for publication in NeuroReport, a rapid turn around publication. This article has been accepted and will be published in the June issue (volume 8, issue 10). The abstract from the article is as follows:

Cortical control of a neuroprosthesis using the electroencephalographic (EEG) signal was investigated. Two able bodied subjects and one individual with a cervical level spinal cord injury were trained to control the amplitude of the beta rhythm of the EEG recorded over the frontal areas. After six months, all subjects exhibited a high level of control over the frontal beta rhythm, being able to use this signal to move a cursor to targets on a computer screen with a greater than 90% accuracy rate. The control over the EEG signal was unaffected by upper extremity movement or electrical activation of the muscles of the forearm and hand, indicating that this signal may be adequate for neuroprosthetic use. To test this, the subject with the cervical level injury used the EEG signal to operate a neuroprosthesis, and was able to effectively manipulate several objects. These findings are important in the future development of cortical control of the hand grasp system.

Plans for Next Quarter

During the next quarter, efforts will be focused on addressing the issue as to whether the signal which is being derived for the control of the neuroprosthesis is actually an EEG signal or if subjects are using facial muscle EMG. This will involve a slight modification of the equipment currently being used. We will also continue work on the development of the EEG-based controller to allow for more functions (i.e. lock/unlock of grasp, grasp selection) to be achieved with the EEG signal.

2. b. iv CONTROL OF HAND AND WRIST

Abstract

We are specifying and developing hardware and software to implement both a laboratory and a portable neuroprosthesis for feedforward neural network control of hand grasp and wrist angle. We are currently investigating operating systems that meet our needs for serial communications with a small and repeatable latency.

Purpose

The goal of this project is to design control systems to restore independent voluntary control of wrist position and grasp force in C5 and weak C6 tetraplegic individuals. The proposed method of wrist command control is a model of how control might be achieved at other joints in the upper extremity as well. A weak but voluntarily controlled muscle (a wrist extensor in this case) will provide a command signal to control a stimulated paralyzed synergist, thus effectively amplifying the joint torque generated by the voluntarily controlled muscle. We will design control systems to compensate for interactions between wrist and hand control. These are important control issues for restoring proximal function, where there are interactions between stimulated and voluntarily controlled muscles, and multiple joints must be controlled with multijoint muscles.

Progress Report

The neural network feedforward control system that was designed and tested for simultaneous control of hand grasp and wrist position can not be implemented in the neuroprosthesis that is used clinically, and we do not have currently a laboratory system that can implement it. During the last quarter, we specified the hardware and software that will be required to implement the system both in the lab, and in a portable neuroprosthesis. Our current plan is to have a laboratory system by September, 1999. We do not expect to have a portable systems within the time frame of this contract.

The requirements of the laboratory system are the following:

1) stimulate all the hand and wrist muscles involved in either grasp mode (lateral or palmar) via either the IRS-8 or IST-10 implantable systems

2) measure via sensors, wrist flexion/extension angle, forearm orientation in the gravitational field, hand grasp opening and hand grasp force

3) compute input/output data sets from steady-state sensor data during constant stimulation with a range of stimulus parameters and combinations of parameters

4) train neural networks with the input/output data

5) implement feedforward control systems for real-time control of hand grasp and wrist angle

6) with the same sensors, measure performance during real-time control

At the present, we envision implementing a laboratory system consisting of a laboratory computer controlling an output stimulus module via a serial interface. All stimulus train control (pulse width and stimulus period on each channel) will be the responsibility of the laboratory computer. This will minimize the hardware development effort in order to start these experiments. We also envision taking maximal advantage of commercially available software (e.g. LabVIEW and MATLAB, including the neural network toolbox) to implement the control systems.

Our principle real-time criterion is that we must communicate with our stimulus module via a serial interface with a repeatable and small latency (on the order of 1-2 ms). During this quarter, we began testing Windows 95, Windows NT, or RT-Linux as possible operating system environments for hosting the real-time control system. Windows NT is preferable over Windows 95 because of the ability to protect individual tasks from crashes in other tasks. However, Windows NT is not designed as a real-time operating system. RT-Linux is a public domain operating system that is reported to meet our needs, but since it is a public domain system, it does not have support, and the number of applications available for it is limited.

To date, we have installed Windows NT in a test computer borrowed from another project. This computer also has a National Instruments MIO board that is required for the latency tests. The latency tests consist of sending a command directly to the MIO board, followed immediately by a message to the serial interface. The time delay between the response measured at the output of the MIO board, and the serial interface is the latency. (This measurement assumes that the MIO board output (D/A) is generated immediately.) We have also learned how to set the interrupt interval in Windows NT to 1 ms. This, along with disabling nearly all other interrupt sources should give us the minimum and most repeatable command generation latency. This strategy will be tested in the next few weeks. If Windows NT does not give us suitable performance, then we will investigate RT-Linux as an operating system. If support is insufficient, or operation does not meet our needs, we will have to pursue the use of another processor, such as a digital signal processor, interfaced to the lab computer. We would like to avoid this, since it will complicate software development and system operation.

Plans for next quarter

We will continue to develop hardware and software specifications, as well as test the capabilities of the commercially available software. We expect to choose an operating system and begin developing software in this quarter.